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Edited by ALAN E. SLATER, M.A., F.R.Met.S.

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EDITORIAL

The present issue of the *Journal* exemplifies the wide field which any Interplanetary Society must regard as its duty to cover. This duty becomes all the more urgent as progress towards our goal is accelerated, as the events of the past year have shown.

First, of course, comes the means of overcoming the earth's gravitation, without which all other problems remain of academic interest only. The rocket motor, whose thermodynamics are explained by Mr. Burgess, has achieved heights at which less than one-millionth of the substance of the atmosphere remains to be penetrated, though it is true that many times the mass ratio of the V2 rocket will be needed to get away from the earth. The purpose of a society such as ours is not to attempt to duplicate these experiments with inadequate resources, but to turn the thoughts of such experimenters towards the goal of interplanetary flight and give them what help it lies in our power to give.

It therefore gave the Society the greatest encouragement to welcome last month Dr. Frank J. Malina, of the Galcit Laboratory, whose rocket experiments were described at length in our last issue. He and his colleagues have been working out figures for a five-step rocket to deposit a 10-lb. "payload" on the moon, and it seems that only the first and last step are likely to present unfamiliar engineering problems, the remaining three being comparable in size to the V2. There appears now no excuse for prolonged inaction pending the development of atomic power.

Mr. Nonweiler's paper on high-speed flight exemplifies another portion of the field covered by the Society. This is only one of a host of diverse lines of research which must be opened up—astronomical, physiological, mathematical, electronic, and so on—once the existence of an effective motive power is established. Here the wealth of expert knowledge which can be drawn upon from the Society's membership can be put to full use, and its new Research Director, Mr. L. R. Shepherd, deserves every support for the scheme which he has drawn up.

Finally, our Society has a duty to perform which, as Mr. Clarke's paper clearly shows, must not be shirked—that of preparing the human mind to accept the implications of interplanetary flight. In a rational world the exploration of space would be a co-operative venture drawing its representatives from the whole human race. If we must have national societies working for the same end, here is a function which can best justify their separate existence.

THE CHALLENGE OF THE SPACESHIP

(Astronautics and its Impact upon Human Society.)

By Arthur C. Clarke

A paper read to the British Interplanetary Society in London on October 5, 1946

I. Introduction

An historian of the twenty-first century, looking back past our own age to the beginnings of human civilisation, will be conscious of four great turning points which mark the end of one era and the dawn of a new and totally different mode of life. Two of these events are lost, probably forever, in the primeval night before history began. The invention of agriculture led to the founding of settled communities and gave Man the leisure and social intercourse without which cultural progress is impossible. The taming of fire made him virtually independent of climate and, most important of all, led to the working of metals and so set him upon the road of technological development—that road which was to lead, centuries later, to the steam engine, the Industrial Revolution, and the age of steel and petrol and surface transportation through which we are now passing.

The third revolution began, as all the world knows, in a squash-court in Chicago, on December 2, 1942, when the first self-sustaining nuclear reaction was started by man. We are still too close to that cataclysmic event to see it in its true perspective, but we know that it will change our world, for better or for worse, almost beyond recognition. And we know, too, that it is linked with the fourth and in some ways greatest change of all—the crossing of space and the exploration of the other planets.

The first spaceships capable of reaching another world may still lie a generation ahead, but the giant rocket is already with us and will soon be carrying men to the limits of the atmosphere and beyond. Though we may doubt whether the American Air Force will land a guided missile on the Moon inside eighteen months, as one of its spokesmen is reported to have rather rashly promised, it will probably not be many years before it achieves this feat. In a report to the Secretary of War, dated November 12, 1945,[1] General Arnold stated that the design of true spaceships is all but practicable to-day, and that research will bring them into being in the foreseeable future. This a broad enough hint to the rest of the world, and behind it one can see the influence of the technicians from Peenemunde who were captured by the Western Allies in the Spring of 1945.

An attempt to construct a philosophy of astronautics is therefore far from premature: it is, if anything, a little belated. In the last few years we have seen the political and ethical chaos produced when a great technical development comes into a world which is unprepared for it. Perhaps it is already too late to redeem past follies: if so, this discussion is rather academic. But if our civilisation is to have a future, then we must see that it does not repeat its earlier mistakes. One of the most important works an organisation such as

the British Interplanetary Society can do is to make the world consider seriously the implications of interplanetary travel, so that its advent is not an overwhelming mental shock but something fully anticipated. I do not suggest that lawyers need start worrying immediately about the ownership of the Moon, but the ownership of space is already a matter of acute practical importance. If a country A fires experimental rockets across its neighbour B, what does B do? The air above B is admittedly its own property, but how far does that jurisdiction extend? There must certainly be some equivalent of the three-mile limit, otherwise, in the course of a day, every country will lay claim to a large portion of the Universe!

II. Ideals and Motives

The ideals of astronautics are new, but the motives and impulses underlying them are as old as the human race. This fact is overlooked by those who criticise our movement, and has equally been overlooked by many who have attempted to defend it against attack. There was a time—not long ago—when the question we were always being asked was "How?" Even before the war that query could be answered in general terms, but there had been no large-scale engineering achievement to support the claims put forward. It is amusing to recall that in those days—which now seem so remote—there were many people who refused to believe that a rocket could work in a vacuum or would ever be able to rise more than a few miles from the Earth.

Times have certainly changed. The power of the rocket has been demonstrated, only too thoroughly. "How?" is a question of which we are no longer afraid: the query which is much more difficult to answer is "Why?" In the past we usually talked glibly of the colossal scientific discoveries which would follow upon the conquest of space, and then made our getaway beneath a cloud of high-sounding rhetoric. Listen, for example, to this extract from an early B.I.S. leaflet:

> "Looking out across immensity to the great suns and circling planets, to worlds of infinite mystery and promise, can you believe that Man is to spend all his days cooped and crawling on the surface of this tiny Earth —this moist pebble with its clinging film of air? Or do you, on the other hand, believe that his destiny is indeed among the stars, and that one day our descendants will bridge the seas of space?"

Now, I am not trying to make fun of that quotation—though as its author I have a perfect right to do so. The viewpoint it represents is an absolutely legitimate one, and I shall return to it later. But the real reason why we wish to cross space has nothing to do with the destiny of man, whatever that may be. It is something at once simpler yet ultimately beyond analysis, for it brings us up against the motives underlying all human conduct.

Some men compose music or spend their lives trying to catch and hold forever the last colours of the dying day, or a pattern of clouds that through all eternity will not come again. Others make voyages of exploration across the world, while some make equally momentous journeys in quiet studies

with no more equipment than pencil and paper. If you asked these men the purpose of their music, their painting, their exploring or their mathematics, they would probably say that they hoped to increase the beauty or the knowledge in the world. That answer would be true, and yet misleading. Very few indeed would give the simpler, more fundamental reason that they had no choice in the matter—that what they did, they did because they must.

So, if we will be honest with ourselves, it is with us. Any "reasons" we may give for wanting to cross space are afterthoughts, excuses tacked on because we feel we ought, rationally, to have them. They are true, but superfluous—except for the practical value they may have when we try to enlist the support of those who may not share our particular enthusiasm for astronautics yet can appreciate the benefits which it may bring, and the repercussions these will have upon the causes for which they, too, feel deeply.

The urge to explore, to discover, to "follow knowledge like a sinking star," is a primary human impulse which needs and can receive no further justification than its own existence. The search for knowledge, said a modern Chinese philosopher,[2] is a form of play. Very well: we want to play with spaceships.

All this, you may say, is not very helpful to those who are trying to convince their friends that there is something in this interplanetary business. However, it is not hard to think of endless and entirely valid "practical" reasons—excuses, if you like—why we should wish to cross space, and some of these we will discuss later. There is no doubt that eventually sheer necessity would bring about the conquest of the other planets. I do not believe it is possible to have a virile, steadily advancing culture limited to a single world, and taking the long term—the very long term—view, we know that our Earth will one day become uninhabitable.

In his book, *The Life and Death of the Sun*, the physicist George Gamow points out that, before its evolution has finished, our sun will become a hundred times as luminous as it is to-day. I am glad to see that he draws the obvious conclusion and visualises the migration of humanity to the outer planets before Earth's oceans have begun to boil.

But the human race will not wait until it is kicked out. Long before the sun's radiation has shown any measurable increase, Man will have explored all the Solar system and, like a cautious bather testing the temperature of the sea, will be making breathless little forays into the abyss which separates him from the stars.

III. The First Decades

To support my thesis, I now have to develop some sort of time-scale. I do this with the greatest misgivings, for prophecy is a dangerous and thankless business, frequently fatal to those who practise it. We have, however, learned by past experience that even the most extravagant forecast seldom overtakes the truth. H. G. Wells once wrote—and was no doubt laughed to scorn for his folly—that the aeroplane might have some influence upon warfare by 1950. Even Wells never imagined that by that date aircraft would not only have become of supreme importance but would have been challenged by still newer weapons.

Another cautious prophet is fortunately still with us. In *Possible Worlds* (published, I believe, in 1927) Professor J. B. S. Haldane placed interplanetary travel in A.D. 8,000,000 or so. Writing to the British Interplanetary Society just before the war, he used the phrase "the next few thousand years." I cannot help thinking that to-day he would be inclined to employ once again that correcting factor of 10^{-3}.

Every major country in the world is conducting rocket research, or will soon be doing so. The British Government is setting up a 1,000-mile-long range in Central Australia: every week the Americans are firing off V2's loaded to the scuppers with cosmic ray telescopes, Geiger counters and anything else that occurs to them—and carrying, of course, the inevitable paintings of Hollywood cuties. When the war ended, the most advanced rocket project was the German A.9-A.10 combination, with a range of 3,000 miles, a payload of 1 ton and a top speed of 8,000 m.p.h.—a third of the velocity needed to escape from Earth. There is no doubt whatsoever that smaller, radio-controlled rockets capable of reaching the Moon can be built with the techniques that exist to-day, though the design of man-carrying machines capable of making a safe landing and returning to Earth is immensely more difficult.

The first guided missile to reach the Moon will probably crash into it around 1950. The public, not realising the problems still to be faced, will expect human beings to follow in a very short time. It will be disappointed. During the subsequent years there will be innumerable short-range flights beyond the atmosphere by man-carrying ships reaching heights of a few thousand miles—and, as I mentioned earlier, raising all sorts of pretty legal problems. But if we have to rely on chemical fuels, it may well require at least twenty years of further experimenting before the first true spaceship lands upon the Moon and returns to Earth.

That brings us up to the 1970's. Any chemically-fuelled spaceships will be unwieldy, fabulously expensive beasts with fuel consumptions measured by the thousand tons for a single voyage. Only a few countries will be able to build them and they will be of scientific value only. There will be no question, for a very long time, of colonisation or voyages to the other planets. But —and it is a very large but—any prophet would indeed be rash if he based his predictions upon the use of chemical fuels alone.

IV. Atomic Power

Here, as in other fields, the great question-mark is atomic energy. In theory, a few pounds of uranium could take a ship weighing many tons to the Moon and back. In practice, we have not the faintest idea how this could be done. It seems possible that some form of enriched, high-temperature pile could be developed to accelerate a working fluid such as hydrogen, helium or some other gas of low molecular weight and so give a propulsive jet. The solution may be very simple: it may come at any time: *it may have come already.*

The application of atomic energy to aircraft propulsion is an exceedingly difficult problem, but it is the one which will pay the greatest dividends. The cost of the fuel is only a small part of the price of electric energy, and we can

easily do without atomic power-stations for a good many years to come. But an atomic aeroplane, capable of unlimited ranges, would be quite another proposition and would revolutionise air transport. Even if the plant and its shielding weighed fifty tons (and there were only six tons of metal in the first Chicago pile) the price would still be worth it to obtain a built-in fuel supply for very large aircraft.

There is no doubt that those concerned fully realise this fact, and we may expect intensive and highly unadvertised research into atomic propulsion for aircraft and rockets. In the United States, it has already been announced that the Fairchild concern has received a government contract for such an investigation.

The race is already under way. Possibly, as I have remarked before, the little radio-controlled chemical rocket, with a payload of only a few pounds, will be the first to reach the Moon. The giant chemically-powered spaceship may never be developed—just as the steam-driven aeroplane was never built, though it might well have been had the petrol engine not come when it did.

Atomic power is hardly likely to advance the conquest of space by more than ten years, but it may make it a really practical proposition almost from the beginning, which otherwise would certainly not have been the case. What is equally important, it will mean that the whole Solar system, and not merely the Moon, will be immediately accessible to Man. It requires relatively little power to reach the other planets if the journey begins from the Moon, but the most economical voyages involve months or even years of "coasting" along orbits curving halfway round the sun. With atomic power these journeys could be cut to a fraction of the time. For example, the "cheapest" journey to Mars—as far as fuel is concerned—lasts 258 days. With an atomic ship, travelling by a more direct route at quite a moderate speed, it need take only two or three weeks.

V. Outward Bound

The last quarter of this century will be an age of exploration such as Man has never known. Before the year 2000 most of the major bodies in the Solar system will probably have been reached, but it will take centuries to examine them all in any detail. Those who seem to think that the Moon is the goal of interplanetary travel should remember that the Solar system contains eight other planets, at least thirty moons and some thousands of asteroids. The total area of the major bodies is about 250 times that of the Earth, though the four giant planets probably do not possess stable surfaces on which landings could be made. Nevertheless, that still leaves an area ten times as great as all the continents of the Earth—without counting the asteroids, which comprise a sort of irregular infinite series I do not propose to try to sum.

This, then, is the future which lies before us, if our civilisation survives the diseases of its childhood. It is a future which some may find terrifying, as no doubt our ancestors found the hostile emptiness of the great oceans. But the men who built our world crossed those oceans, and overcome those fears. If we fail before the same test, then our race will have begun its slide

into decadence. Remember, too, that when Drake and Raleigh set sail into the unknown they said goodbye for years to their homes and everything they knew. Our children will face no such loneliness. When they are among the outermost planets, when Earth is lost in the glare of the sun and the sun itself is no more than the brightest of the stars, they will still be able to hear its voice and to send their own words in a few hours back to the world of men.

I shall mention no more dates, but here is one rather striking thought I would like to leave with you. Orville Wright, the first man to fly in a heavier-than-air machine, is now in the middle seventies. If he lives to be as old—for want of a better word—as George Bernard Shaw, he will see at least the beginnings of the conquest of space.

VI. The New Sciences

I intend now to consider the effects that interplanetary travel must have upon human institutions and ideas. The most obvious and direct result of the crossing of space will be a revolution in almost all branches of science. I will not attempt to list more than a few of the discoveries we may make when we can set up research stations and observatories upon the other planets. One can never predict the outcome of any scientific investigation, and the greatest discoveries of all—the ones which will most influence human life—may come from sciences as yet unborn.

Astronomy and physics will, of course, be the fields of knowledge most immediately affected. In both these sciences there are whole areas where research has come to a dead end, or has never even started, because our terrestrial environment makes it impossible.

The atmosphere, which on a clear winter night looks so transparent, is in reality a coloured filter blocking all rays beyond the ultra-violet. Even in the visible spectrum the light that struggles through the shifting strata above our heads is so distorted that the images it carries dance and tremble in the field of the telescope.

An observatory on the Moon, working with quite small instruments, would be many times as effective as one on Earth. Far greater magnifications could be used, and far longer exposures employed. In addition, the low gravity would make relatively simple the building of larger telescopes than have ever been constructed on this planet.

In physics and chemistry, access to vacua of unlimited extent will open up quite new fields of investigation. The electronic scientist may well look forward to the day when he can build radio tubes a mile long, if he wishes, merely by setting up his electrodes in the open! It is also interesting to speculate whether we may not learn more about gravity when we can escape partially or wholly from its influence.

The prospect of building stations in space, circling the Earth like tiny moons in orbits beyond the atmosphere, is one that has a peculiar fascination. Such stations were first proposed as refuelling depots for spaceships, but even if that need never arises they would have other most important applications. Meteorological observatories in space could see at a glance the weather over half the planet, could watch in detail the movement of storms and rain areas.

Few people, particularly in these islands, would deny the immediate practical importance of this! Indeed, really accurate forecasting may have to wait until we can get the meteorologists out into space.

The space-station has one other application of very great importance, for as I have pointed out elsewhere[3] it could provide a very simple and economical means of world-wide television broadcasting. As is well known, the reliable range of a television transmitter extends barely beyond the horizon. A dozen stations, at least, would be needed to cover a country as small as Britain, and a world service would be completely out of the question. Yet three repeater stations circling the Earth could provide a steady, reliable service from Pole to Pole with little more power output than the present London transmitter.

VII. Psychology and Politics

But the first direct results of astronautics may be less important than its indirect consequences. This has proved true in the past of many great scientific achievements. Copernican astronomy, Darwin's theory of evolution, Freudian psychology—these had few immediate practical results but their effect on human thought was tremendous.

We may expect the same of astronautics. With the expansion of the world's mental horizons may come one of the greatest outbursts of creative activity ever known. The parallel with the Renaissance is very striking, and I would like to take it further had I the time and the training. "In human records," wrote the anthropologist J. D. Unwin,[4] "there is no trace of any display of productive energy which has not been preceded by a display of expansive energy. Although the two kinds of energy must be carefully distinguished, in the past they have been . . . united in the sense that one has developed out of the other." Unwin continues with this quotation from Sir James Frazer: "Intellectual progress, which reveals itself in the growth of art and science . . . receives an immense impetus from conquest and empire." Interplanetary travel is the only form of "conquest and empire" now compatible with civilisation. Without it, the human mind, compelled to circle forever in its planetary goldfish bowl, must eventually stagnate.

We all know the narrow, limited type of mind which is interested in nothing beyond its town or village, and bases all its judgements on those parochial standards. We are slowly—perhaps too slowly—evolving from that mentality towards a world outlook. Few things will do more to accelerate that evolution than the conquest of space. It is not easy to see how the more extreme forms of nationalism can long survive when men begin to see Earth in its true perspective as a single small globe among the stars.

There is, of course, the possibility that as soon as space is crossed all the great powers will join in a race to claim as much territory as their ships can reach. So far, I am glad to say, there has been no interplanetary flag-waving in Britain. But though Imperialism (in the worst sense of the word) is dying in this country, by a strange irony of fate it shows signs of revival on the other side of the Atlantic. "It has even been suggested," we read in the *Observer*,[5]

"that if the United States wants to be the 'Number One' power of the atomic age it must occupy the Moon with man-carrying rockets." I do not think we need take this sort of sixteenth-century buccaneering too seriously, but it represents a threat which it would be unwise to ignore. The menace of interplanetary imperialism can be overcome only by world-wide technical and political agreements well in advance of the actual event, and these will require continual pressure and guidance from the organisations which have studied the subject. Whether we like it or not—and most of us probably won't—we will sooner or later find ourselves lobbying as energetically, and I hope as effectively, as the American atomic scientists. Let us therefore get our own ideas fully organised before we too stand blinking in the sunlight amid the ruins of our ivory towers.

The Solar system is rather a large place, though whether it will be large enough for so quarrelsome an animal as *homo sapiens* remains to be seen. But it is surely reasonable to hope that the crossing of space will have a considerable effect in reducing the psychological pressures and tensions of our present world. Much depends, of course, on the habitability of the other planets. I do not expect that very large populations will, at least for many centuries, be able to subsist outside the Earth. There may be no worlds in the Solar system upon which men can live without mechanical aids, and some of the greatest achievements of future engineering will be concerned with shaping hostile environments to human needs.

VIII. Knowledge and Wisdom

We must not, however, commit the mistake of equating mere physical expansion, or even increasing scientific knowledge, with "progress"—however that may be defined. Only little minds are impressed by sheer size and number. There would be no virtue in possessing the Universe if it brought neither wisdom nor happiness. Yet possess it we must, at least in spirit, if we are ever to answer the questions which men have asked in vain since history began.

Perhaps analogy will make my meaning clearer. Picture a small island inhabited by a race which has not yet learned the art of making ships. Looking out across the ocean this people can see many other islands, some much the same as its own but most clearly very different. From some of these islands, it is rumoured, the smoke of fires has been seen ascending—though whether those fires are the work of men no-one can say.

Now these islanders are very thoughtful people, and writers of many books with such resounding titles as: *The Nature of the Universe*, *The Meaning of Life*, *Mind and Reality*, and so on. Whilst admiring their enterprise, I do not think we should take their conclusions very seriously—at least until they have gone a little further afield than their own coral reef. Said the last Poet Laureate[6]:

> Wisdom wil repudiate thee, if thou think to enquire
> WHY things are as they are or whence they came; thy task
> is first to learn WHAT IS.

That task the human race can scarcely begin to undertake while it is still Earthbound.

IX. Other Worlds and Minds

Every thoughtful man has often asked himself: is our race the only intelligence in the universe, or are there other, perhaps far higher, forms of life elsewhere? There can be few questions more important than this, for upon its outcome may depend all philosophy—yes, and all religion too.

The first discovery of planets revolving round other suns, which was made in that *anna mirabilis* 1942, has changed all ideas of the plurality of worlds. Planets are far commoner than we had believed: there may be thousands of millions in this Galaxy alone. Few men to-day would care to argue that Earth must be the only abode of life in the whole of space.

It is true—it is even likely—that we may encounter no other intelligence in the Solar system. That contact may have to wait for the day, perhaps ages hence, when we can reach the stars. But sooner or later it must come.

There have been many portrayals in literature of these fateful meetings. Most science-fiction writers, with characteristic lack of imagination, have used them as an excuse for stories of conflict and violence indistinguishable from those which stain the pages of our own history. Possibly because I was never trained in what are laughingly called the humanities,* I do not believe that war must inevitably arise from contact between Mankind and other races, if such there be.

Remember the penny and the postage stamp that Sir James Jeans balanced on Cleopatra's needle.[7] The obelisk represented the age of the world, the penny the whole duration of man's existence and the stamp the length of time in which he has been slightly civilised. The period during which life will be possible on Earth corresponds to a column of stamps hundreds of yards—perhaps a mile—in height.

Thinking of this picture, we see how extremely improbable it is that the question of interplanetary warfare can ever arise. Any races we encounter will almost certainly be subhuman or superhuman—more likely the latter, since ours must surely be one of the youngest cultures in the Universe. Only if we score a bullseye on that one stamp in the mile-high column will we meet a race at a level of technical development sufficiently near our own for conflict to be possible.

But if the Universe does hold species so greatly in advance of our own, then why have they never visited Earth? There is one very simple answer to this question. Let us suppose that such races exist: let us even suppose that, never having heard of Einstein, they can pass from one end of the Galaxy to the other as quickly as they please.

That will help them less than one might think. In ten minutes, a man may walk along a beach—but in his whole lifetime he could not examine every grain of sand upon it. For all we know, there may be fleets of survey ships diligently charting and recharting the Universe. Even making the most optimistic assumptions, it is hardly likely that our world would have been visited in the few thousand years of recorded history.

* A very naughty remark, but why should all the rudeness come from the Arts side?

Perhaps, even at this moment, there is in some rather large filing system a complete report on this planet, with maps which to us would look distorted but still recognisable. That report would show that though Earth was teeming with life, it had no dominant species. However, certain social insects showed considerable promise, and the file might end with the note: "Intelligence may be emerging on this planet. Suggest that intervals between surveys be reduced to 100,000 years."

Very well, you may ask, suppose we encounter beings who judge, condemn and execute us as dispassionately, and with as little effort, as we spray a pool of mosquito larvae with DDT? I must admit that the possibility exists, and the logical answer—that their reasons will no doubt be excellent—is somewhat lacking in appeal. However, the prospect seems remote. I do not believe that any culture can advance, for more than a few centuries at a time, on a technological front alone. Morals and ethics must not lag behind science, otherwise the social system will breed poisons which will cause its certain destruction. I believe therefore that with superhuman knowledge must go equally great compassion and tolerance. In this I may be utterly wrong: the future may yet belong to forces which we should call cruel and evil. Whatever we may hope, we cannot be certain that human aspirations and ideals have universal validity. This we can discover in one way only, and the philosophical mind will be willing to pay the price of knowledge.

X. Philosophy

I have mentioned before how limited our picture of the Universe must be so long as we are confined to this Earth alone. But the story does not end here. Our impressions of reality are determined, perhaps more than we imagine, by the senses through which we make contact with the external world. How utterly different our cosmologies would have been had Nature economised with us, as she has done with other creatures, and given us eyes incapable of seeing the stars! Yet how pitiably limited are the eyes we do possess, tuned as they are to a single octave in an endless spectrum! This room in which we are gathered is drenched with radiations, from the microwaves which we have just detected as emanating from sun and stars, to the cosmic rays whose origin is still one of the prime mysteries of modern physics. These things we have discovered within the last generation, and we cannot guess what still lies beneath the threshold of the senses—though recent discoveries in paranormal psychology hint that the search may be only beginning.

The races of other worlds will have senses and philosophies very different from our own. To recall Plato's famous analogy,[8] we are prisoners in a cave, gathering our impressions of the outside world from shadows thrown upon the walls. We may never escape to reach that outer reality, but one day we may hope to meet other prisoners in adjoining caves, whose shadows will be very different from ours and from whom we may learn more than we could ever do by our own unaided efforts.

These are deep waters, and it is time to turn back to the shore, to leave the distant dream for the present reality of combustion-chamber pressures,

servo-control mechanisms and cotangential orbits. Yet I make no apology for discussing these remote vistas at some length, if only to show the triviality of the viewpoint which regards astronautics as a schoolboy adventure of no more real value than the scaling of some hitherto inaccessible mountain. The adventure is there, it is true, and that is good in itself—but it is only a small part of a much greater whole.

Not so short-sighted, but equally false, is the view expressed by the Oxford theologian C. S. Lewis, who has written of would-be astronauts in this unflattering fashion: "The destruction or enslavement of other species in the Universe, if such there are, is to these minds a welcome corollary." Mr. Lewis's ideas appear to have been culled in the cloisters of Magdalen College from a perusal of the pages of "Staggering Stories"—not, I think, evidence upon which any jury would convict. There is certainly no sign of such an outlook in British astronautics, and, as I have already shown, a race such as ours, which has only possessed steam-power for a century and a half, is not likely to have a chance of enslaving any other species it may encounter.

Yet, in case there are any to whom such a prospect appeals, I would point out that Empires—like atomic bombs—are self-liquidating assets. Dominance by force leads to revolution, which in the long run, even if indirectly, must be successful. Humane government leads eventually to self-determination and equality, as the classic case of the British Empire has shown and is still showing. Commonwealths alone can be stable and enduring, but Empires must always contain the seeds of their own dissolution.

The desire to give a comprehensive picture of the outcome of astronautics has compelled me to range—not unwillingly—over an enormous field. However, I do not wish anyone to think that the possibilities we have been discussing need come in this century, or the next, or the next. . . . Yet any of them may arise, at any time, as soon as the first ships begin to leave the Earth. Man's first contact with other intelligent races may lie as far away in time as the building of the Pyramids—or it may be as near as the discovery of X-rays. But prophecy is almost always conservative, and on the whole it is better to be too early in one's anticipations than too late.

XI. Interstellar Travel

Of this, at least, we may be fairly certain. Barring accidents—the most obvious of which I need not specify—the exploration of the planets will be in full swing as this century draws to its close. To examine them in any detail, and to exploit their possibilities fully, will take hundreds of years. But Man being what he is, when his first ship circles down into the frozen wastes of Pluto, his mind will already be bridging the gulf still lying between him and the stars.

Interplanetary distances are a million times as great as those to which we are accustomed in everyday life, but interstellar distances are a million-fold greater still. Before them even light is a hopeless laggard, taking years to pass from one star to its neighbour. How Man will face this challenge I do not know: but face it one day he will. Professor Bernal was, I believe, the

first to suggest that one solution might lie in the use of artificial planets,[9] little self-contained worlds embarking upon journeys which would last for generations. Olaf Stapledon has expanded this theme in one of the greatest of his fantasies,[10] but the thought of these tiny bubbles of life, creeping from star to star on their age-long journeys, carrying whole populations doomed never to set foot upon any planet, never to know the passage of the seasons or even the interchange of night and day, is one from which most minds will recoil in horror. However, those who make these journeys will have outlooks very different from our own, and to them such voyages may be great and glorious adventures.

Yet perhaps, after all, the velocity of light is not an absolute limit that can never be surpassed. During the war I often found it rather tantalising to think that the electromagnetic field patterns moving up and down sundry copper tubes in my keeping were doing so at one and half times the speed of light—and could even reach an infinite velocity if some careless mechanic upset the adjustments. There was, of course, a catch in this, as anyone who has had dealings with wave-guides will know. Still, the fact remains that at least three "phenomena" in the physical world can attain unlimited speeds, and, indeed, are incapable of travelling as slowly as light.*

These speculations, intriguing though they are, will hardly concern Mankind in this century. We may, I think, confidently expect that it will be a hundred years at least before confinement to the Solar system produces very marked signs of claustrophobia.

XII. Conclusion

Our survey is now finished. We have gone as far as is possible, at this moment of time, in trying to assess the impact of astronautics upon human affairs. I am not unmindful of the fact that fifty years from now, instead of preparing for the conquest of the outer planets, our grandchildren may be dispossessed savages clinging to the fertile oases in a radio-active wilderness. Yet we must keep the problems of to-day in their true proportions. They are of vital—indeed, of supreme—importance, since they can destroy our civilisation and slay the future before its birth. But if we survive them, they will pass into history and the time will come when they will be as little remembered as the causes of the Punic Wars. The crossing of space—even the sense of its imminent achievement in the years before it comes—may do much to turn men's minds outward and away from their present tribal squabbles. In this sense the rocket, far from being one of the destroyers of civilisation, may provide the safety-valve that is needed to preserve it.

I would like to emphasise this point, which may be of the utmost importance. By providing an outlet for man's exuberant and adolescent energies, astronautics may make a truly vital contribution to the problems of the present world. Space-flight does not even have to be achieved for this to happen. As soon as there is a general belief in its ultimate possibility, that belief will

* The other two being light when moving through a metal of refractive index < 1, and the de Broglie waves associated with an electron, whose speed $= c^2/v$ where v is the velocity of the electron. The same equation applies in the case of the field patterns quoted above, v then being the speed at which the *signal* moves along the wave-guide.

begin to colour men's psychological outlook. This is particularly true of the active—even aggressive—minds of those peoples, such as the Americans, British and Russians, for whom the problem is most acute. In many ways, the very dynamic qualities of astronautics are in tune with the restless, expansive mood of our age.

In this talk I have tried to show that the future development of mankind, on the spiritual no less than the material plane, is bound up with the conquest of space. To what may be called—using the words in the widest sense—the liberal scientific mind, I believe these arguments to be unanswerable. The only real criticism that may be raised against them is the quantitative one that the world is not yet ready for such changes. It is hard not to sympathise with this view, which may be correct, but I have given my reasons for thinking otherwise.

There are, of course, a great many people who regard the whole subject of interplanetary travel with distaste or even with hostility, believing it to be inherently bad. If they still retain those convictions I do not propose to argue further with them: they are welcome to their beliefs and we will part with polite if slightly frigid bows. Yet I think we should expect support both from our friends and from our enemies, since the latter may reasonably hope that when we have departed into space we shall leave them at last in peace.

The future of which we have spoken is now being shaped by men taking instrument readings amid the roar and scream of harnessed jets, by men building up circuits in quiet laboratories, by men with calculating machines in offices and studies all over the planet. In this work many of us will play our part, but let us never become so obsessed by the mere technology of the problem that we forget the goal to which it is leading. The toil of a generation of scientists and engineers will be needed before the first men set foot upon the Moon. These things cannot be done by dreaming alone—but the vision must come before the achievement and the truly creative mind must hold the balance between the two, never letting one dominate the other. T. E. Lawrence once wrote[11]: "All men dream; but not equally. Those who dream by night in the dusty recesses of their minds wake in the day to find that it was vanity: but the dreamers of the day are dangerous men, for they may act their dream with open eyes, to make it possible. This I did."

Let us, also, echo those words.

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(11) T. E. Lawrence: *Seven Pillars of Wisdom.*

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DISCUSSION.

Mr. A. V. CLEAVER, from the Chair, expressed general agreement with the paper just read and threw it open to discussion.

Mr. R. A. SMITH asked whether any suggestions had been advanced about the possibility of Man living on other planets. Though Venus and Mars might soon be visited, it may be two or three hundred years before these planets can be made habitable.

Mr. L. J. CARTER said that, though people can be educated in one or two sciences by first-hand experience, it has now become necessary to learn by the experience of others through the medium of lectures, etc. When scientific knowledge has been still further increased by the exploration of space, how long will our grandchildren have to be at school?

One speaker asked, in view of the possibility of international rivalry, whether we should bring the matter before the United Nations or Unesco before interplanetary travel actually starts.

Mr. J. MULLIN suggested that the attempt to find out more about conditions on other planets would at least give the world an objective other than a domestic one. As to artificial planets making voyages so long as to cover many generations, would those who arrive at the destination be at all representative of the earth's inhabitants? And how many generations would it take?

Mr. CARTER raised an economic question: we exist primarily for work, therefore without work we cannot exist. So man will only seek to reduce his work in order to li e, whereas if he tries to live on other planets he would have to work harder than before.

A speaker raised the point that, on the earth, quicker travel means increased danger—witness aeronautics. But another speaker replied that *some* danger is a necessary part of our existence. In the past, the explorer has always been followed by the exploiter, and, unless some interplanetary control is established, the same thing will happen again. Someone will find out on Mars or Venus how to dispose profitably of a bottle of whisky!

Mr. L. R. SHEPHERD favoured a direct rather than an academic approach to this problem.

Mr. SMITH, discussing the likelihood of conflict, pointed out that the Moon is a bigger place than Danzig, and what we really have to fear is conflict between man and man over various bits of the universe. The British Interplanetary Society should try to contact others with the object of building up a body of opinion to restrain those who would exploit interplanetary flight for the purpose of national rivalries. He quoted an example.

Another speaker, commenting on the extent to which members were worrying about possible conflicts, gave a warning that if we continue to worry about such things we shall never get to the planets.

Mr. CARTER said that it was unfair to impose responsibility upon scientists for the misuse of their achievements.

Mr. CLEAVER asked if the answer was not that the administration of human affairs must become an applied science.

Dr. A. E. SLATER asked to have some doubtful points cleared up. The two planets belonging to other stars, discovered in 1942, had been quoted as evidence for the existence of many other planets in the universe; but these two were ten or more times as big as Jupiter, which is itself incapable of supporting life as we know it, on account of physical conditions resulting from its large size.

He believed there were good arguments in favour of the extreme unlikelihood of intelligent life arising even on a specially favourable planet like the earth. For instance, one plausible theory of the evolution of man attributes it to the growth in recent geological times of the Himalayas, which gradually cut off the moist Indian winds from the forests on the Central Asian plateau, thus forcing the monkeys to come down from the disappearing trees and evolve a more efficient brain to cope with an increasingly difficult situation. But for this geographical accident,

man might never have evolved at all; in fact, Julian Huxley, in his recent book *Evolution*, concludes that if the human race were wiped out now, intelligent life would probably never again evolve on the earth.

Furthermore, even when intelligent life has evolved, the chances appear to be all against its developing a civilisation. *Homo sapiens* with his present brain capacity has existed on the earth for a quarter of a million years, yet only in the last ten thousand years has he become civilised. It looks as if civilisation were an accident too; and combining this with the accident of intelligence, we find that we must balance an almost infinite unlikelihood of a civilisation arising on any planet, against the likelihood of an almost infinite number of planets, before we can decide whether any other civilisation is likely to exist in the universe.

With regard to Mr. Clarke's belief that a culture limited to this world cannot continue to advance indefinitely: if a graph be drawn showing the rate of technical advance of our civilisation, the resulting curve shows a continually steeper rate of climb, with no sign of the increase of rate ever falling off.

Finally, regarding the statement that "only little minds are impressed by sheer size and number," which is only too true, are we not ourselves in danger of being accused of worshipping mere distance?

Mr. H. E. Ross did not agree regarding the changelessness of man over the last 250,000 years. About 50,000 years ago Neanderthal Man, virtually a different species, lived on the earth. The first true men appeared twenty-five to thirty thousand years ago: they were the Aurignacians, whose last traces are still to be found in the population of the Canary Islands. Leading from that, we must consider the possibility that man himself may change when he crosses space, adapting himself to new conditions; on Jupiter's astronomical surface, for instance, gravity is 2·6 times that on the earth. It seemed to the speaker that, a large number of centuries from now, several different species of man would evolve, suited to life on the various planets, and any interplanetary wars would therefore arise between different species of man.

Mr. HARRIS pointed out that we know very little about what happens in even the first 20,000 feet of the atmosphere. Beyond that, would not meteorites and other hazards have to be reckoned with?

Another speaker expressed anxiety about what public opinion would think if the first space ship to leave the earth were to crash, and its crew fail to return alive. With regard to the rarity of life on other planets, he suggested that the gases known to exist in the atmospheres of Jupiter and Saturn might have been produced by, for instance, nitro-bacteria.

Reply.

Mr. A. C. CLARKE, replying to the discussion, issued a warning that this part of his discourse, unlike his paper, was unprepared, and therefore he did not wish it to be used in evidence against him at a future date!

Replying to Mr. Smith, he said that we have no idea of conditions on Venus. On Mars it is almost certain that man could not exist unprotected, and the first colonists would have to live in self-contained cities. Possibly man would produce deliberate changes in himself in order to live there.

Regarding the question raised by Mr. Carter, the multiplication of knowledge imparted in education was a problem which must be answered anyway, irrespective of the development of interplanetary travel.

Several speakers had raised the question of interplanetary rivalries; but any races we might meet on other worlds would be the equivalent of either aborigines or angels. Mr. Clarke considered it premature to try to influence governments; the time for that would be when the first guided missile reached the moon. What if it should place a flag there? As an example of what we might do then, the American Federation of Atomic Scientists had shown the way by its activities in educating the public. But at the present time people would just laugh at us, and we must first get them slowly accustomed to the idea of the exploration of space.

With regard to Mr. Mullin's remarks on contacting other civilisations, the discovery of a better civilisation than ours should make us go back home resolved to do something about our own. Mr. Mullin had also asked about interstellar voyages: we should be able to get from one star to another in about twenty years, if a really efficient atomic drive was developed, so there was no need to budget for many generations of travellers. Another possibility was suspended animation, on which some work had been done by scientists. To the more distant parts of the Galaxy, voyages of the order of a quarter of a million years would be needed.

Concerning Mr. Carter's fear that economic considerations might inhibit the desire for space-travel, Mr. Clarke said that he hoped we should never become ruled by economics alone. It is, or should be, the slave of mankind and not its master. This was the view expressed by the late Lord Keynes, who looked forward to the day when the economic problem was settled and we could get down to the business of living.

The dangers of space-travel, mentioned by one speaker, were not, in Mr. Clarke's opinion, greater than those of flying, and possibly not as great as those of travel by road! It was difficult to grasp the emptiness of space. One way of appreciating it was to realise that it would be extremely rare for one ship ever to "sight" another, even by radar. The alleged dangers of collision with meteors, and of harmful radiations, appeared to be grossly over-rated.

Regarding the possible exploitation of other planets by rival interests, for this reason Mr. Clarke favoured the ultimate creation of an International Interplanetary Society—though he hoped that someone could think of a more euphonious title! He had always doubted whether the name "British Interplanetary Society" was really in keeping with the vastness of its object; an "East Ham Interplanetary Society" would hardly be more parochial! We had made some contact with the corresponding societies in America, some of whom were more interested in pure rocketry than in space-flight and needed to be converted. At least one citizen of that country, however, wanted the Moon to become a "Forty-ninth State."

In reply to Dr. Slater, the recently discovered planets were heavier, and not necessarily larger, than Jupiter, and a third had now been discovered. These planets circled some of the nearest of the stars, and only their nearness and large size had led to their discovery. Statistically there must, therefore, be a great many more planets of all sizes from large to small. Regarding the question of life on other planets, we should probably know the answers within our lifetimes—which was an excellent reason for not dogmatising on the subject. There is very good evidence of vegetation on Mars, so that of the three planets whose surfaces we can actually see (Earth, Mars and Moon), Nature appears to have scored two hits out of three. One could imagine enormous extremes between which life of some kind was possible.

Concerning technical progress, Mr. Clarke said we must not assume a continuous increase. The curve was probably a "growth curve," which eventually levels off again after the steepest part of the ascent, at the bottom of which we are now situated.

The answer to any criticism that we are impressed by "mere size and number"—and distance—is that what we are really seeking is complexity and richness of experience.

Mr. Ross had suggested conflicts between different adaptations, or subspecies, of man; but each adaptation would be suited to one particular planet and would find life impossible on another. There might, nevertheless, be psychological tensions which could lead to conflict.

Answering Mr. Harris's concern lest the first spaceship might cause a severe set-back to astronautics by crashing, Mr. Clarke stated that there might never be a "first ship to the Moon"; instead there would be a series of successive approximations. So he could see no possibility of one single disaster causing an agitation for the banning of space-travel, though that might happen as a result of the development of an anti-scientific movement.

Regarding the possibility of life on the major planets, the trouble with Jupiter was not the magnitude of gravity but the enormous pressure at the bottom of an atmosphere thousands of miles deep.

THERMODYNAMICS OF THE ROCKET MOTOR

By Eric Burgess

Considered from the point of view of power/weight ratio, the rocket is the most powerful engine known to Mankind; and mechanically it is, perhaps, one of the simplest heat engines in existence, for its power is applied as a direct thrust without any conversions of energy through reciprocating or rotating parts. Essentially the motor consists of a combustion chamber in which the fuels are mixed and burned. The chemical energy which the fuels have, due to their composition, is changed in this chamber to heat energy in the products of combustion, which energy appears as the high temperature and pressure of the gases in the combustion chamber. By means of a special expansion nozzle, the heat energy of the gases is changed into the kinetic energy of the exhaust stream, thus giving a replacement of the pressure head by a velocity head. Developed in conformity with Newton's Third Law of Motion, the force of propulsion results from the acceleration of the effluent stream, because the force necessary to produce this acceleration is accompanied by an equal but opposite force on the rocket itself.

There are two main types of rocket motor in use at the present time, these being the liquid fuel and solid fuel rockets respectively. During the recent war, German technicians developed the bi-fuel motor extensively, ultimately producing the Walter 109-509 and other similar units, and the V2 motor. Although the solid fuel rocket will continue to be employed for rocket-assisted take-off and for small military projectiles, it is the liquid fuel rocket which will be the object for extensive development in the coming years. It is, therefore, with the liquid fuel type of rocket motor that this paper is mostly concerned, although it is to be remembered that many of the principles discussed apply equally as well to the solid fuel type.

In order to formulate the thermodynamical principles of the liquid fuel rocket, it is necessary in the beginning to establish its cycle of operation. First the fuel is injected into the combustion chamber, and during this process it undergoes a reduction in pressure, for the input pressure must, of course, be maintained at a sufficiently high value above that in the combustion chamber in order to ensure an adequate and continual supply of fuel. When it is remembered that the motor of the V2 rocket consumed two-and-a-half hundredweights of fuel per second, it can be appreciated that this is no mean problem. Turbine pumps operated by secondary fuels can, however, be used for the purpose of obtaining an effective and comparatively simple solution.

Normally there are two fuels, one being an oxidiser and the other a hydrocarbon of some type. Oxidisers which have been employed in addition to liquid oxygen and liquid air are hydrogen peroxide and fuming nitric acid. In most modern rocket systems, the hydrocarbon is circulated round the blast chamber and nozzle, thus acting as a coolant and also carrying back to the combustion chamber any heat which would otherwise be lost by conduction through the chamber walls. In many motors, too, the fuels are pre-mixed before injection, and this produces a more complete mixture which in turn

encourages faster and better burning. Quite often the mixing takes place, as in the V2, by arranging the injectors in clusters so that the fuel is sprayed into the chamber through a concentric circle of holes surrounding the single oxidiser inlet. A process known as spontaneous disruption takes place in the case of liquid oxygen and a hydrocarbon, and the latter breaks up into innumerable tiny droplets, thereby materially assisting the propagation of the flame through the combustible mixture.

After injection, the fuels, in a liquid state, must be further heated to the temperature at which a change to the gaseous state occurs. The latent heat for this change of state must then be supplied, followed by further heating to bring the mixture to the temperature at which combustion is initiated and will spread rapidly through the comburants. The result is an exothermic reaction which, after the first shock of combustion has taken place, settles down and proceeds under conditions of constant pressure. The temperature may reach extremely high values, and it will be shown later how this can cause a loss in efficiency due to the speeding up of reverse reactions and consequent thermal dissociation in the products of combustion. The combustion in the chamber must be as complete as possible, but many things happen to reduce the efficiency by prolonging the period of burning. The most important factor in this respect is the length of time during which the fuels are in the combustion chamber. It has to be appreciated that there is a continual flow of comburants through the chamber, and if burning is slow, due to bad mixing or other causes, combustion may not be completed before the gases enter the exhaust nozzle. This reduces the efficiency because the total possible heating effect has not been achieved inside the combustion chamber. At the nozzle entrance the exothermic reaction should be completed and all the available chemical energy changed into heat. Subsequent burning in the nozzle passage is detrimental to the efficient working of the motor and may, indeed, lead to complete failure due to what is known as motor burn-out, a condition in which the metal walls of the nozzle are rapidly eroded by the swiftly moving gas stream.

The combustion chamber thus acts as a constant-pressure source of supply of working substance for the nozzle. It is, moreover, in the nozzle that the main acceleration of the gases occurs. There, the available heat is changed into the kinetic energy of the effluents in accordance with the well-known equation of continuity. The expansion is theoretically adiabatic, in which no external work is done; the whole mass of gas entering the nozzle being expanded to a low pressure, and the value of the exhaust pressure determining the amount of conversion obtained and thus the jet velocity. During this process, the random molecular motions of the hot gases are changed into a unidirectional one away from the rocket. The ideal nozzle will, in addition, not only expand the working substance, but will also expand it to the ambient pressure and temperature.

The working process of the rocket motor is thus shown in Figures 1 and 2, in which the pressure-volume and heat-entropy diagrams are plotted. On the pressure-volume diagram (Figure 1), AB represents the heating of the working substance under conditions of constant pressure, which produces, of course, an increase in volume equal to $v_2 - v_1$. BC represents the adiabatic expansion

from chamber pressure to exhaust pressure. Because no external work is done during the expansion, the area ABCE represents the heat energy which is changed to kinetic energy during the cycle. In practice, however, the expansion is not truly isentropic, but is described as "adiabatic and resisted," so that the actual expansion curve follows the line BD. Assuming that expansion under these conditions is continued again to ambient pressure, a longer nozzle is required, because the reheating of the effluents due to friction and turbulence results in a greater volume at the discharge pressure. The area BCD shows the heat lost as far as conversion to kinetic energy is concerned.

In Figure 2, AB is once more the curve showing the heating along the line of constant pressure (combustion chamber pressure). The heat and entropy of the working substance increase until point B is reached. At that point combustion is completed, and the products are then passed into the nozzle.

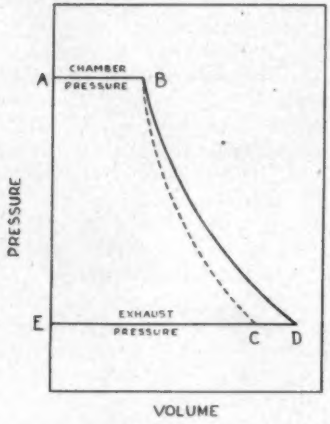

FIG. 1

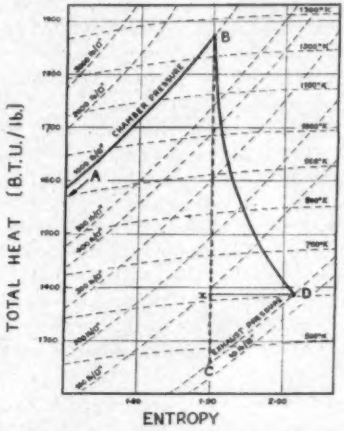

FIG 2.

An isentropic expansion through the nozzle would be shown by BC, but the actual expansion follows BD to the same line of discharge pressure. xD now represents the increase in entropy during the expansion process, and xC the heat lost. It can also be seen from the figure that the temperature of discharge is greater than it would be if the expansion were adiabatic and isentropic.

The thermodynamic working cycle of the rocket engine having been thus established, it becomes possible to investigate the various parts of this cycle more thoroughly.

Combustion under conditions of Constant Pressure.

Earlier in this paper it has been mentioned that the exothermic chemical reactions in the combustion chamber take place under conditions of constant pressure. For the purpose of any calculations it is necessary to assume, not

only that the chamber pressure is constant, but also that it is uniform. Having made these assumptions, it is possible to analyse the burning process, some idea of which can be gained from the fundamental principles of physical chemistry. Whereas the general algebraic solution of the problem is well-nigh impossible, a numerical result for a particular case can be obtained by a number of successive approximations, somewhat in the same manner as the determination of the burning in internal combustion engines.

From the laws of the conservation of energy it is known that the energy of an isolated system is constant. The vigorous chemical action in the combustion chamber liberates large quantities of heat, and it can thus be said that the so-called chemical energy of the fuel is being transformed into heat energy. The maximum amount of this which can be obtained from a chemical reaction is known as the total heat, and the value can be ascertained by carrying out the reaction under such conditions that no external work is done. As in practice no mechanical work is done in the combustion chamber, and the kinetic energy of the gas stream passing through the chamber is small enough to be neglected, the chemical energy should thus all appear as heat energy in the products of combustion. The relation between the heat energy in the products of combustion and the total heat available is known as the combustion chamber efficiency, about which more will be said later.

The amount of the chemical reaction which takes place in a given fuel mixture is governed by the law of mass action, and is proportional to the active mass, that is the molecular concentration of each of the reacting substances. Many actions which take place in rocket motors are what are known as reversible. To take an example: in the use of hydrogen and oxygen as fuels, when a certain combustion temperature is reached there will be as much steam breaking down into oxygen and hydrogen as there is being formed from these elements at that temperature. The system is then said to be in a state of chemical equilibrium. Where a reverse reaction can take place under the same combustion chamber conditions as those needed for the burning of the fuel, then combustion can never be complete. Some reactions are, of course, irreversible, such as the burning of magnesium in oxygen, and in cases like this the reaction proceeds to the complete exhaustion of one or both of the fuels. This is why light metals in the finely divided state have been proposed as ideal rocket fuels, for not only do they overcome the difficulties of incomplete burning in this respect, but they also release more heat than any other fuel combination, and should hence produce high jet velocities. The great difficulty is, however, in the feeding of the metal fuel into the combustion chamber, but it has been suggested that the use of a colloidal suspension process may overcome this difficulty.

Although some fuel combinations are not really reversible, a similar effect occurs and manifests itself as thermal dissociation, This is the case where the fuel is a hydrocarbon used in conjunction with oxygen. The forward reaction produces steam and carbon-dioxide and is not reversible. At the temperature of combustion, nevertheless, steam and carbon-dioxide undergo an endothermic reaction, splitting up and absorbing heat, thus reducing the combustion efficiency of the motor.

The most important point about the condition of chemical equilibrium is that even a slight change of the temperature, pressure or concentration of the substances in the combustion chamber will displace the equilibrium. The displacement occurs in such a manner as to relieve the effects of the stress thus imposed on the system. From van't Hoff's law of mobile equilibrium can be established the fact that if the temperature is increased, the action which absorbs heat will predominate until a new equilibrium is reached. Similarly, if the pressure is increased, the reaction which reduces the volume will operate to displace the equilibrium.

In rocket motors, the jet velocity depends to a great extent upon the absolute temperature inside the combustion chamber, and for high jet velocities this temperature must be as high as possible. This results in the loss of heat due to the favouring of the endothermic reaction, and must be countered by other methods such as an increase in pressure, as will be seen later.

It thus becomes necessary to calculate the initial concentrations of fuels which correspond to a final equilibrium capable of developing the greatest possible jet velocity. The problem is really not to obtain complete combustion but rather to achieve maximum jet velocity. The numerical calculations needed to obtain results are tedious and complex, for it is necessary to commence with stoichiometric amounts, ascertaining, for the considered fuel, the heat yield and equilibrium temperature at various chamber pressures. Five or six simultaneous equations must be solved in each case, and a table of equilibrium constants for the considered reaction is required. It is then possible to establish the resulting jet velocity if it is assumed that the available heat is completely converted into kinetic energy, and hence to determine the effects of pressure on the actual jet velocity.

Following this it is necessary to repeat the whole process for various percentages of excess of one of the fuels over the amount theoretically required for complete combustion. A graph can finally be plotted to show how pressure and excess of fuel can change the jet velocity. In Figure 3 an approximate curve is shown for the hydrogen-oxygen reaction, and variations in pressure are shown to have a marked effect upon the excess of fuel required to give maximum actual jet velocities. In fact an excess of hydrogen has more effect than an increase in pressure in displacing the equilibrium so as to produce an advantage in jet velocity. Even at quite low pressures, for example, it is possible to obtain a reasonable amount of the energy theoretically available. On the same figure are shown the percentage losses in jet velocity at the various chamber pressures, and it is apparent that these are not very great.

With some fuel combinations, however, where the volume of the products is greater than that of the vapourised comburants, an increase in pressure has adverse effects upon the reaction and displaces the equilibrium in the wrong direction. It is virtually impossible to produce general tables or graphs for the combustion effects in rocket motors. The individual designer, therefore, has to make separate calculations regarding each rocket motor which itself has to be designed for specific fuels and operating conditions.

Of prime importance in motor design is the ratio of combustion chamber

volume to nozzle throat area, for this is a measure of the time available for combustion to take place. The longer the fuels are in the chamber then the more complete will be the burning and the greater will be the efficiency at this stage. Although the shape of the chamber, the method of injection and the type of fuels used also affect the burning, it is possible to give an approximate indication of the efficiency that can be expected for various ratios. Figure 4 shows the percentage loss in theoretical maximum jet velocity, and also the percentage efficiency, for various relationships between chamber volume and nozzle throat area. The data for the graph were obtained from empirical results of Sänger, the American Rocket Society and the German war rockets. It can be seen that a ratio of at least 100 inches is required if losses at this stage are to be maintained at a reasonable value, and it is important to remember that high ratios are more easily obtained with large motors because, of course,

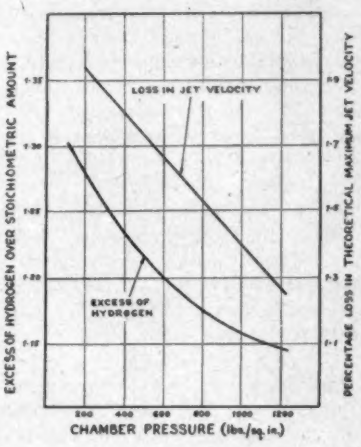
LOSS IN JET VELOCITY
EXCESS OF HYDROGEN
EXCESS OF HYDROGEN OVER STOICHIOMETRIC AMOUNT
PERCENTAGE LOSS IN THEORETICAL MAXIMUM JET VELOCITY
200 400 600 800 1000 1200
CHAMBER PRESSURE (lbs./sq. in.)

FIG. 3

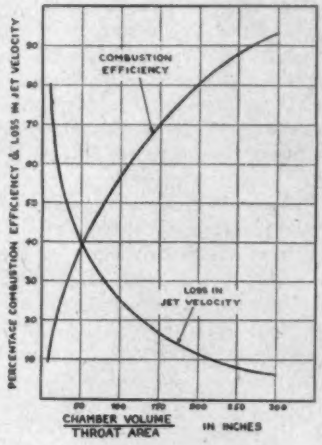
COMBUSTION EFFICIENCY
LOSS IN JET VELOCITY
PERCENTAGE COMBUSTION EFFICIENCY & LOSS IN JET VELOCITY
CHAMBER VOLUME / THROAT AREA
IN INCHES

FIG. 4

the volume increases more rapidly than does the area. The reason so many of the early rocket motors were so inefficient was that they were too small for combustion to be completed in the chamber.

In practice the effects of thermal dissociation (except in the case where carbon dioxide is a main constituent of the products of combustion), and burning losses, are not so important as others which are now to be considered. Of far greater importance in determining the efficiency of a rocket motor as a heat engine is the temperature inside the combustion chamber and the temperature of the discharged gases. These temperatures determine the adiabatic heat drop which in turn enables one to ascertain the amount of heat which is available for conversion to kinetic energy and hence capable of giving a propulsive effect.

Expansion in the Rocket Nozzle.

It has been stated earlier that, heat energy having been generated in the combustion chamber, this must result in an acceleration of the products of combustion away from the rocket if a thrust is to be developed. If a simple orifice is used to allow the gases to escape from the chamber, an acceleration does take place, but optimum conditions are not realised because only a limited amount of the available energy of the gas is used. Incomplete expansion results and the pressure of discharge is only about half that in the chamber, while the velocity of the gases is restricted to that of sound within them at the same temperature and pressure. Although expansion proceeds to ambient pressure (i.e. that surrounding the rocket) after the effluents leave the orifice, lateral expansion of the gas stream prevents full thrust from being obtained.

If the products of combustion are to be fully expanded to ambient pressure, a specially designed convergent-divergent nozzle is required which makes possible a more complete utilisation of the heat energy and considerably improves the jet velocity. The narrowest part of the nozzle is known as the throat, and the wide open part away from the combustion chamber is the mouth. The convergent part is usually just a well-rounded entrance, but the divergent part is much longer, conical in shape, and has a taper of between 6° and 15°.

Determined by the areas of the mouth and throat is the expansion rate of the nozzle, and it should be such that the gases, when discharged from the mouth, are at a pressure equal to that surrounding the rocket. The pressure in the gas stream is characterised by a rapid drop from chamber pressure to critical pressure at the throat—that is about half chamber pressure—followed by a more gradual reduction as the effluents pass through the divergent cone. If the mouth area is too large, over-expansion results, and shock waves reduce the efficiency. If too small, the size of the nozzle mouth prevents full expansion and losses again occur; but as these are partially recoverable, they are not so serious as in the case of over-expansion.

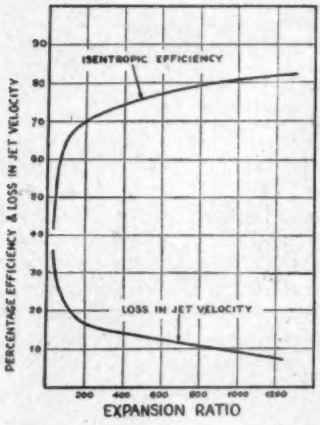

FIG. 5

The amount of heat energy which can be utilised to produce thrust depends upon the adiabatic heat drop along the nozzle, which is governed by the expansion ratio; that is, the relation between the chamber and discharge pressures. The adiabatic expansion laws enable this to be expressed in terms of temperature change along the nozzle and the absolute chamber temperature, and from this the well-known efficiency equation of the Carnot cycle is evolved. In Figure 5 is shown the percentage loss in theoretical jet velocity due to this cause which is, of course, bound up with the Second Law of Thermodynamics and the availability of heat for doing work. It affects the thermal efficiency and may be described as a

sub-division of that efficiency, being normally referred to as the ideal isentropic efficiency. From the graph it is apparent that at low chamber pressures—that is, below an expansion ration of 100—the loss in jet velocity is quite considerable due to this cause alone.

In the rocket motor operating at sea-level—that is, in an atmosphere at normal pressure—the thermal efficiency is severely limited. If a reasonable expansion ratio is to be used, the chamber pressure must be at least 1,000 pounds per square inch, but practical considerations of structural and pumping difficulties make it necessary to restrict the chamber pressure to 50 atmospheres (735 lbs. per sq. inch) at the most. However, if the rocket is employed in the upper reaches of the terrestrial atmosphere, the rapid fall of outside pressure with height enables a much greater expansion ratio to be obtained, with a consequent improvement in the isentropic efficiency. Optimum conditions will be realised when the discharge from the nozzle is made into the vacuum of space.

In practice, as has been earlier pointed out, the expansion of the gases through the nozzle is not truly isentropic, because frictional and other losses cause a reduction in the heat available for acceleration of the efflux. There is, indeed, a gradual growth of entropy as the flow proceeds along the nozzle, and it is usual, therefore, to define another sub-efficiency of the rocket motor under the name of nozzle efficiency.

For any heat engine there is an equation of steady flow which applies, and which states that the change in enthalpy plus the change in kinetic energy is equal to sum of the external work done and the heat lost to the surroundings. In rockets it has been mentioned that no external work is done, and it is also usual to consider the gases as having no general velocity at the time of entering the chamber. Theoretically the expansion should be adiabatic so that the heat lost to the surroundings would be zero too, but in fact a certain amount of heat is lost by conduction and radiation. The processes through which the comburants pass should, moreover, be reversible, and again this is not so in practical motors. The final velocity of the jet is determined by the actual heat drop and not by the adiabatic one.

The efficiency of the expansion process is thus given by the actual heat drop less the heat lost to the surroundings, divided by the adiabatic heat drop. There is, moreover, a ratio between the kinetic energy developed in the gas stream by an irreversible adiabatic expansion and that of a reversible one for the same expansion ratio which can be expressed in terms of the temperatures in the nozzle. This is the actual temperature drop along the nozzle divided by the theoretical one as calculated from the ratio of nozzle throat area to nozzle mouth area. A definite loss occurs, therefore, and another sub-efficiency must be allowed for.

Thermal Efficiency

The thermal efficiency of a rocket motor has thus been shown to depend upon many things. Essentially, of course, it is the ratio between the total heat yield from the fuel and the kinetic energy in the jet. First there is the efficiency with which the chemical energy of the fuel is changed into heat energy during exothermic reactions. This is known as the *combustion chamber*

efficiency and it depends primarily upon the amount of dissociation, and the time which the fuels take to pass through the chamber. By careful choice of fuels and design of chamber, there is no reason why this efficiency should not reach 75 per cent.

Then there is the *ideal isentropic efficiency* which depends upon the expansion ratio of the rocket nozzle. At sea-level it is unlikely that this efficiency can be made to exceed 50 per cent., but if the rocket is used in the upper atmosphere reasonable values of up to 80 per cent. may be obtained.

Finally, the *nozzle efficiency* is the ratio between the actual temperature drop along the nozzle and the theoretical one. Friction losses, turbulence, and other losses will reduce this to about 90 per cent. in well-designed nozzles, but as the jet velocity increases, the losses increase also. In practice it may be possible to obtain an efficiency in this stage of only 75 per cent.

The *thermal efficiency* is the product of these sub-efficiencies and it can readily be seen that it can only be in the region of 28 per cent. under sea-level conditions, but that an improvement will result if the rocket motor is used in atmosphere of reduced pressure. As a power unit in the stratosphere or the upper atmosphere, the rocket can be even 45 per cent., and possibly 50 per cent. efficient. If the rocket is, therefore, considered purely from the point of its being a heat engine, then it is only likely to supersede other methods of propulsion when it is applied to vehicles which are designed for use in the upper stratosphere. Notwithstanding this fact, there are, nevertheless, many uses to which the rocket can be put in the lower atmosphere, where the loss in efficiency is more than compensated by the extreme effectiveness of this method of propulsion.

HIGH SPEED FLIGHT

By T. R. F. Nonweiler, B.Sc.

(*Supersonics Division, Royal Aircraft Establishment.*)

Summary of a lecture given to the British Interplanetary Society in London on November 2nd, 1946.

The problems which confront the aerodynamicist in the subject of high speed flight are many and various. The attainment of high speeds is one of the principal objects in the development of rocket aircraft and missiles, so that these problems must of necessity concern the rocket engineer to some extent.

The object of the following discussion is to review these problems in a concise manner; no complete answer can be given in the space available, as each subject is highly specialised, but a preliminary stocktaking is of some value as the Society enters the field of high speed research.

Fundamentals

The characteristic flight of a missile, winged or otherwise, depends on two main aerodynamic parameters: lift, the sustaining force, and drag, the resisting force. The value of these forces has a bearing on the structural weight, the performance, the stability and the control characteristics of the missile in question.

In considering the pattern of the air flow past wings and bodies we have to distinguish between the cases in which the speed is low and the air behaves as an incompressible fluid, or when it is subsonic but sufficiently large to bring about local changes in the density of the air, and finally when the body is travelling through it at supersonic speeds.

Incompressible Flow

When the speed of flow past a body is sufficiently small we may regard the air as an incompressible fluid—one in which the density is the same throughout the field—and the flow pattern, for example, roughly resembles that of the same body through water. This type of flow need not concern us greatly here, and is dealt with in many books on hydrodynamics.

Compressible Flow

In this case, as the name implies, the air undergoes changes of density in the course of its flow. Fortunately, a simple rule, due to Prandtl and Glauert, exists which shows that the forces on a two dimensional body in compressible flow are the same as those in incompressible flow times a factor $(1/\sqrt{1 - M^2})$ where M is the so-called Mach Number—the ratio of the free stream velocity past the body to the speed of sound.

Transonic Flow

The Prandtl-Glauert rule would imply that the forces on a body are infinite at $M = 1$, when the body travels with the speed of sound. This, of course, is not true, and the rule breaks down when there are local regions of accelerated flow past the body which are supersonic. This happens when the free stream Mach Number is less than unity, at a value called the "critical" speed.

The critical Mach Number heralds the approach of mixed regions of sub- and super-sonic flow, which are not readily analysed by mathematical means, and which persist over the entire transonic range of speeds.

Investigations of this interesting region of flow are handicapped by the fact that wind tunnels are limited in the degree to which they can simulate free stream sonic conditions, due to the difficulty of tunnel wall design, the unknown effects of tunnel wall interference, and the premature choking of flow with a model in position. So that free flight experiments are practically the only answer.

Supersonic Flow

Established supersonic flow is characterised by the presence of shock waves at the leading and trailing edges of bodies in such a stream. A shock wave is merely a finite region in which variations in velocity, pressure and density are intense; in passing through a shock wave the velocity component of the stream perpendicular to the shock is reduced, and the component parallel to the wave remains unchanged.

Thus, in passing through a shock wave inclined obliquely to the free stream, the air suffers a change in direction as well as a reduction in velocity. For each Mach Number there is a maximum angle of deflection, and provided the inclination of the surface to the free stream is less than this critical angle the

required change in flow direction can be accommodated by the presence of an oblique shock.

If, on the other hand, the deflection is greater, as required at the nose of a bluff body, the shock wave detaches itself from the nose of such a body and moves forward, taking up a position ahead. In such a case the inclination of the shock to the free stream is perpendicular, the property of such a "normal" shock being that it reduces the free stream velocity to a subsonic value with a corresponding density rise.

To avoid this state of affairs it is advisable to use body and aerofoil shapes involving only small incidences to the main stream, and so with sharp edges or points as opposed to the usual subsonic streamline profiles.

Under these conditions a simple linearised two-dimensional theory of supersonic flow was developed by Ackeret, which predicts that the pressure at a surface inclined at a small angle ϵ to the main stream, is given by

$$\left(\frac{2\epsilon}{\sqrt{M^2-1}}\right)\frac{1}{2}\rho V^2 \quad \ldots\ldots\ldots\

local shock waves occur on the wing surface), and the last term denotes the induced drag, or that due to wing incidence. At supersonic speeds

$$C_D = C_f + \frac{C_{D_0}}{\sqrt{M^2 - 1}} + \frac{1}{4} C_L^2 \sqrt{M^2 - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

so that aspect ratio is again unimportant, but C_{D_0}, the drag coefficient of the aerofoil at zero incidence, is proportional to the (thickness/chord) ratio squared and is no longer negligible. Thus thin wing sections are particularly beneficial in reducing high speed drag.

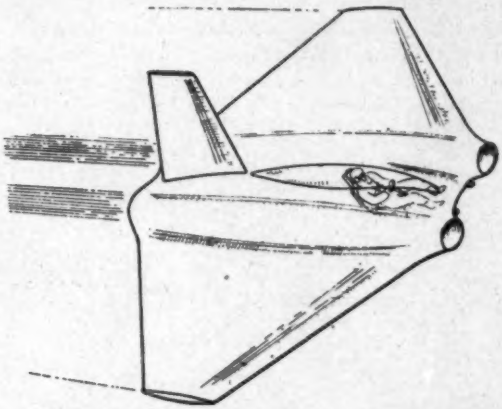

FIG. 1. A typical "Delta" aircraft with triangular wing shape.

(3) AERODYNAMIC CENTRE. The aerodynamic centre of a wing is that point about which the moments on the aerofoil are constant; at subsonic speeds it is at a distance of ¼ chord behind the leading edge. On an uncambered (symmetrical) aerofoil its position corresponds with that of the centre of pressure. Likewise, at supersonic forward speeds the position of the aerodynamic centre and the pressure centre is at the ½ chord point, so that the wing is inherently more stable.

(4) DOWNWASH. At subsonic speeds the lift forces acting on a wing manifest themselves by deflecting the air flowing off the trailing edge of the wing downwards, producing a downwash on the tailplane and so reducing its effective angle of incidence. This is no longer true in supersonic flight.

Stability Changes in Transonic Flight

A tightening-up of stability in going from subsonic to supersonic flight is evinced from the following considerations:—

(1) The movement of the aerodynamic centre from ¼ to ½ chord point.

(2) The lack of downwash at the tail at supersonic speeds giving greater tailplane effectiveness.

(3) The disappearance of aspect ratio effects at supersonic speeds, usually giving greater effectiveness to the tailplane which is normally of lower aspect ratio.

If we eliminate a tailplane altogether we leave only the first effect; this can in turn be reduced but not eliminated by the use of a very low aspect-ratio triangular wing platform (the so-called "Delta" wing). (Fig. 1.)

Furthermore, we can place the tailplane before the wing, which makes effect (2) negligible, and uses the third effect due to the low aspect ratio of the "foreplane" to cancel the first. By this means the stability change may be entirely eradicated. (Fig. 2.)

Over-stability is as much a fault as instability, as an aircraft which is very stable requires very large moments from its controlling surfaces to produce a change in direction.

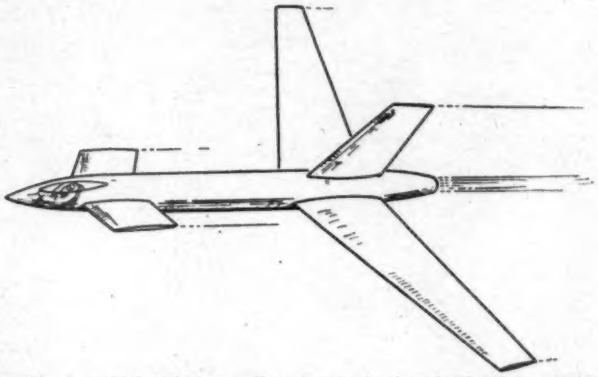

FIG. 2. A typical rocket-propelled supersonic aircraft of tail-first design.

Transonic Flight

At the moment we regard the transonic region as constituting a gradua change-over from subsonic to supersonic conditions. Thus on conventionallyl designed aircraft and winged missiles there is a general change in longitudinal stability and a loss in camber effect which together cause a nose-down change in moments at high M. This normally requires a large elevator surface to trim, and the tendency is, therefore, to use all-moving tail surfaces.

The effects, whilst still present, are less marked if symmetrical wing sections are used, and the aircraft is designed to have the same stability in both sub- and super-sonic flight.

The conditions above the critical Mach Number are not only complicated by moment changes and a drag rise, but also by a rapid loss in lift over the wing section—a phenomenon known as the "shock stall." There is no reason to suppose that this loss will be so great as to render sustained flight at sonic speeds impossible; the little theoretical work that there is suggests that the lift at a given incidence will reach a minimum a little before $M = 1$ and thereafter rise again.

The rise in drag-coefficient on a wing continues to a maximum just in

excess of the speed of sound, when it begins to decrease with Mach Number much in the same manner as predicted by Ackeret's relations.

The Delay of Compressibility Effects

There are a number of ways in which we may delay these high speed effects, but of course, none by which they can be entirely eliminated. Of these the following may be quoted:—

(1) Reduction in wing (thickness/chord) ratio
(2) Use of small aspect ratio wings.
(3) Use of symmetrical wing sections.
(4) Movement of the position of maximum thickness on the wing section back to about 0·4 or 0·5 chords behind the leading edge.
(5) Reduction of the trailing edge angle.
(6) Use of sharp leading edges.
(7) Mounting of the tail surface at the same incidence to the undisturbed stream as the wing.
(8) Introduction of sweep-back or sweep-forward.

Of these methods by far the most important are the first and the last. All methods are alike in reducing the maximum lift obtainable at low speeds, but all combine to delay the onset of the compressibility drag rise and shock stall.

Sweepback

The effect of sweepback may be envisaged by considering the flow over a yawed wing; the lift on such a wing is reduced by a factor $\cos^2\beta$ (where β is the angle of yaw) compared with that on an unyawed wing, and the drag (excluding that due to skin friction) by a factor $\cos\beta$. Moreover, the Mach Number across the aerofoil is reduced by a factor $\cos\beta$, so that a straight wing with a critical Mach Number of M_c will have a critical speed of $M_c \sec\beta$ in the yawed condition. This indicates a substantial delay of high-speed troubles and a large reduction in drag.

In fact, the application of sweep-back to wing shapes implies a swept **V**-shaped wing, in which the centre section is effectively unswept, and the saving is, as a result, less than that suggested above. If a fuselage is housed at the centre section we can approach very near the yawed wing conditions by correct design of the body-wing junction.

The main defect of sweepback is a low-speed trouble: the maximum lift coefficient is smaller than on straight wings, landing (high-lift) aids are less effective, and when the stall does occur it does so first at the tips—which leads to wing drop.

There are various ways of overcoming this last-mentioned embarrassment: nose flaps on the outboard half span, hinged about the leading edge and opening downwards from the under surface, can be particularly effective and also serve as a high lift aid. Normal methods such as washout of the wing incidence, the provision of differential ailerons, and leading edge slots, are to a certain extent effective, but are undesirable in supersonic flight.

The phenomenon of tip stall is brought about by a spanwise drift in the boundary layer over a swept wing, due to spanwise velocity component. For

this reason, fins placed half-span outboard cause the boundary layer to pile up just inboard of their position, inducing a first stall in this region. This is particularly useful as it prevents a dynamic tip stall (as for example in high speed manœuvres) when landing aids would not normally be extended.

There is some indication that tip stall may only be present on *tapered* swept wings, but taper is a necessary inauguration to ensure stability in yaw and lateral forces at high incidence and low speeds.

Nor does tip stall appear to be present on the very low aspect-ratio Delta wing shapes, where the entire flow is three-dimensional.

Sweepforward

In general, sweepforward is just as beneficial in delaying compressibility effects as sweepback, and the tip stall is replaced by a root stall which is less dangerous. However, the sweep-forward leads to a natural instability in both yaw and roll, which is particularly marked at high speeds due to the high wing drag. Thus, sweepforward is generally unsuited to high speed aircraft.

Control Problems of High Speed Subsonic Flight

Associated with the occurrence of the shock stall is a loss in control effectiveness which might eventually lead to a complete reversal of control forces, rendering the aircraft completely uncontrollable.

There are two solutions to this problem: either to use all-moving surfaces instead of the usual hinged type, or else rely on jet or spoiler control.

The all-moving control surface loses effectiveness at high speeds, but there is no reason to suppose that this should amount to reversal any more than it is reasonable to suppose that the lift of wings should be reversed at transonic speeds.

The application of this scheme to aileron control implies the inauguration of movable or hinged wing tips.

Whilst directional control is possible with the use of drag spoilers at all speeds, lateral rake-spoilers (depending on spoiling the flow over one wing tip, reducing the local lift forces, and so producing roll) are very ineffective at supersonic speeds, but are effective up to high subsonic Mach Numbers.

Jet control, either by exhaust or jet-vanes, has the great advantage of being entirely independent of aircraft speeds, and is most effective when the lift forces on the rest of the aircraft are small, as at and above the shock stall.

Body Effects

Whilst the drag forces on projectile shapes are widely appreciated, the effects of body lift are perhaps not so widely known.

The lift of a projectile-shaped body contributes a lift coefficient at supersonic speeds of about 3α based on the maximum frontal area of the body, if α is its incidence. This figure applies to highly tapered projectile noses and flat bases; it is rather higher if the nose is blunter, and lower if the speed is subsonic.

The position through which this force may be deemed to act—the pressure centre—is roughly at the nose of the projectile in subsonic flight, moving back to a point about half the nose length aft in supersonic flight. The lift of projectiles results almost entirely from the nose; but if the nose length is short

compared with the total length, the pressure centre is at a distance of $\frac{1}{4}$ the total length behind the nose.

The drag of a projectile is considerably reduced by the introduction of highly tapered heads; but an even more important factor than head drag is base drag, which can be considerably reduced if the base is boat-tailed or tapered to a point like the head. This is most effective at transonic Mach Numbers, but less so at higher speeds, above M = 4, when a near-vacuum forms at the base whatever its shape. As well as reducing drag, the effect of full base taper is to halve the lift and move the pressure centre—generally forwards.

Aerodynamic Skin Heating

In general, skin heating depends chiefly on the conduction into the skin of heat from the boundary layer and the radiation *from* the skin tending to balance the former. Boundary layer conduction varies as the density of the air, the velocity of the body through it, and the temperature difference of the skin and the stagnation temperature of the air given by the relation

$$\text{Stagnation temperature} = T_o + \frac{kV^2}{2JC_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

where T_o is the ambient air temperature, C_p its specific heat at constant volume, J is Joule's equivalent, V the velocity, and k is an experimental factor usually rather less than unity.

Thus conduction into the surface decreases with increasing altitude proportionally to the air density; and at high altitudes in an atmosphere rich in hydrogen, the specific heat of the air is very much larger, so that the stagnation temperature is also reduced.

Radiation from the skin to the space around, however, depends only on skin temperature and is independent of atmospheric density. At all altitudes radiation from the boundary layer into the skin is completely negligible, and in a dry atmosphere radiation from the air to the skin is also unimportant.

Thus, at high altitudes the increasing importance of radiation compared with conduction implies that the theoretical stagnation temperature would never be reached on the skin even in prolonged level flight; and in a finite time the rate of heat transfer into the body is so small that only fractions of the final equilibrium temperature are even attained.

This point was illustrated on the V2, which reached a maximum skin temperature during descent of 600° C., compared with the theoretical maximum stagnation temperature of 1200° C.

To conclude, the danger of skin heating can always be avoided by going high enough; and it is best to make the surface of the high-speed missile as near an effective black-body radiator as possible, and to use poor conducting material. The effects of solar radiation, near the earth, at least, are not prohibitive.

Wing Structure Weight

On high speed aircraft the desirability of using low-drag and high-speed wing designs as outlined above must always be balanced against the structural

weight involved, which indirectly affects the amount of fuel which can be carried, or its percentage of the all-up weight.

Wing weight may be analysed as follows:—

(1) Bending components: weight varies as $(\text{span})^2$ (thickness);
(2) Shearing components: weight varies as span;
(3) Stiffness components: weight varies as $(\text{span} \times \text{area})/(\text{thickness})^2$;
(4) Rib weight: varies as (thickness $\times$ area).
(5) Skin weight: varies as area.

Thus, for a given area it pays to have as small a span as possible, i.e. a small aspect ratio, which we have noted is permissible and even desirable from an aerodynamic point of view; and also in general a fairly large thickness. Thickness also determines the high-speed drag of an aerofoil and evidently a compromise solution is necessary on this score.

A successful aerodynamicist should always bear in mind the effect of his requirements on the other aspect of design work!

CORRECTIONS AND ADDENDA

In the June issue of the *Journal* (Vol. 6, No. 1) the following corrections should be made:—

A SURVEY OF ATOMIC POWER. On page 7, in the first group of formulae, beginning of third line, Np^{239}_{93} should read Np^{239}_{93}.

In the second group of formulae, beginning of second line, Th^{233}_{91} should read Th^{233}_{90}; and at begiuning of third line, Pa^{233}_{94} should read Pa^{233}_{91}.

SOUNDING ROCKET RADIO SONDE. On page 44, the following references were inadvertently omitted and should be added to those at the bottom of the page:—

Diamond, H., and Others. A Method for the Investigation of Upper Air Phenomena, and its Applications to Radio Metereorography, *Proc. I.R.E.*, Oct., 1938.
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Short Wave Weather Balloons, *Sh. Wave & Tele.*, July, 1937.
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